Interpretation of the high energy IceCube data

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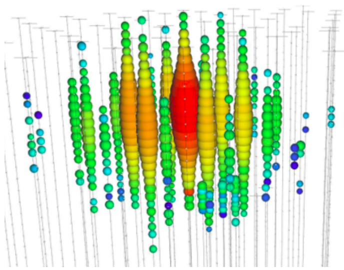

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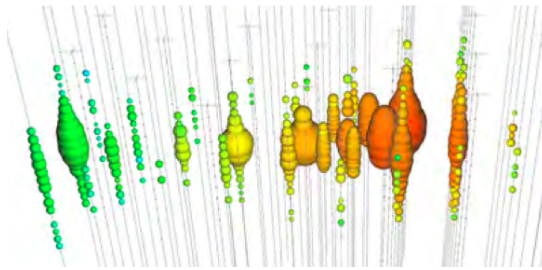

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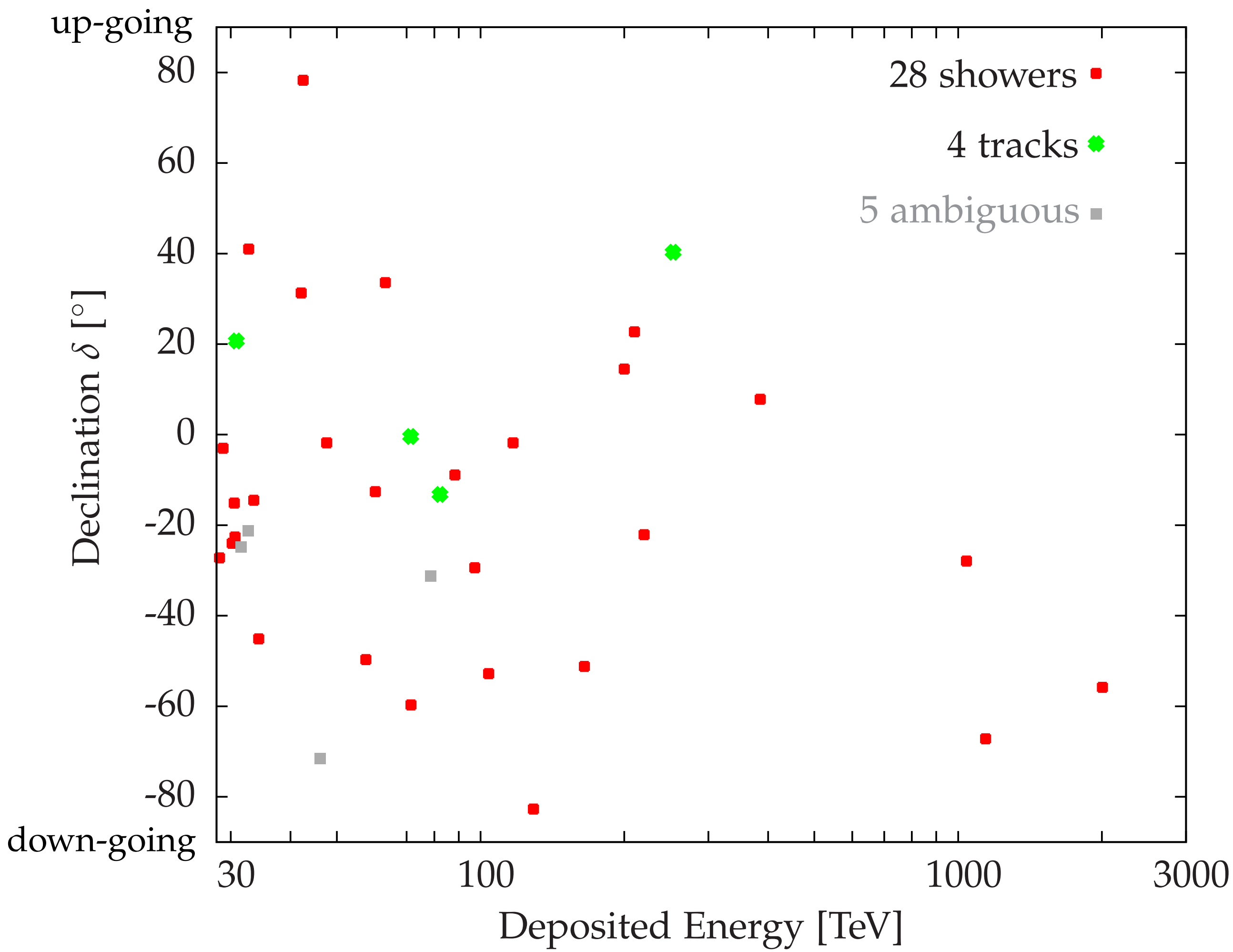
Motivation | IceCube events

- 32 events of $E \gtrsim 30$ TeV in $T = 988$ days (2010–2013) [IceCube '14]

  (+5 μ background compatible with 8.4 ± 4.2 expected: *ambiguous*)



$\Rightarrow$ atm + astrophysical !!

Motivation **IceCube events**

- The event rate is neutrino flavor (ν) and interaction (int) dependent:

$$N_{\nu,\text{int}} = TN_A \int \mathrm{d}\Omega \int_{E_\text{thres}} \mathrm{d}E_\nu \, M_\text{eff}^{\nu,\text{int}}(E_\nu) \frac{\mathrm{d}\phi_\nu}{\mathrm{d}\Omega \mathrm{d}E_\nu} P_\text{surv}^\nu(\theta_z, E_\nu) \int_{y_\text{min}}^{y_\text{max}} \mathrm{d}y \frac{\mathrm{d}\sigma_\text{int}}{\mathrm{d}y}$$

$$\mathrm{d}\Omega = 2\pi \, \mathrm{d}\cos\theta_z \qquad\qquad y = 1 - E'/E_\nu \text{ (inelasticity)}$$

- Two interpretations depending on which interactions/astrophysical flux:

  1. Usual: SM physics and $E_\nu^{-\gamma}$ flux (*fit* to the excess)

  2. Ours: New physics (*generic*) and cosmogenic neutrino flux (*predicted*):

     – Model of TeV gravity:

     $$\langle y \rangle \sim 10^{-5} \text{ (eikonal interactions)}$$

     – Cosmogenic neutrinos from scattering of CRs off CMB radiation

     $$E_\nu \sim 10^8 - 10^{10} \text{ GeV}$$

Motivation | Consistent model of TeV gravity with $n = 1$

- Hybrid model in 5D [Giudice, Rattazzi, Wells '11]

$n = 1$ *almost* flat extra dimension with a *slight* warping and $\overline{M}_5 \sim 1$ TeV:

$\overline{M}_P = M_P/\sqrt{8\pi}\,, \quad \overline{M}_D = M_D/(2\pi)^{n/(2+n)}$

		[Flat case]
4D Planck mass	$\overline{M}_P^2 = \frac{\overline{M}_5^3}{k}\left(e^{2k\pi R} - 1\right)$	$[2\pi R\,\overline{M}_5^3 \quad (\text{limit } k \ll R)]$
KK mode sep	$m_c \sim k$ (free)	$[R^{-1}, \quad R \sim (10^{-27}\text{ GeV})^{-1} \sim 1\text{ AU (excluded)}]$
curvature	$k \ll \overline{M}_5$ and $k > R^{-1}$	

Gravity gets strong at distances $r \lesssim m_c^{-1}$

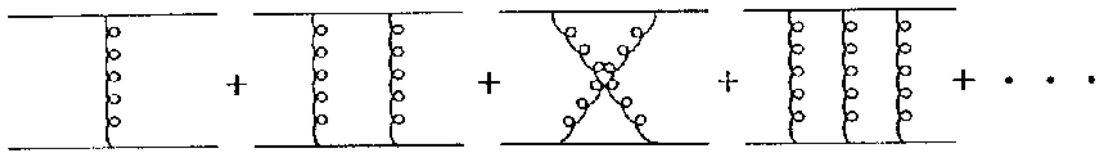
[e.g. $m_c = 50$ MeV $= (4\text{ fm})^{-1}$ for $\overline{M}_5 = 1$ TeV $\Rightarrow$ size $R = (5\text{ MeV})^{-1} = 40$ fm]

– For $Q = \sqrt{y\hat{s}} \sim r^{-1} \gg m_c$ gravity is 5D and XD $\sim$ flat. Otherwise $e^{-m_c/Q}$ supp

– At a given $\sqrt{\hat{s}}$ there are less KKs but more strongly coupled than in flat case

Motivation | **Consistent model of TeV gravity with $n = 1$**

- Phenomenology for $\sqrt{\hat{s}} \gg M_5$ (transplanckian collisions):
  - Black hole formation (BH): short distance, ν destroyed
  - Eikonal (eik): long distance, quasielastic (low Q^2), higher σ, *classical* gravity (dominant)



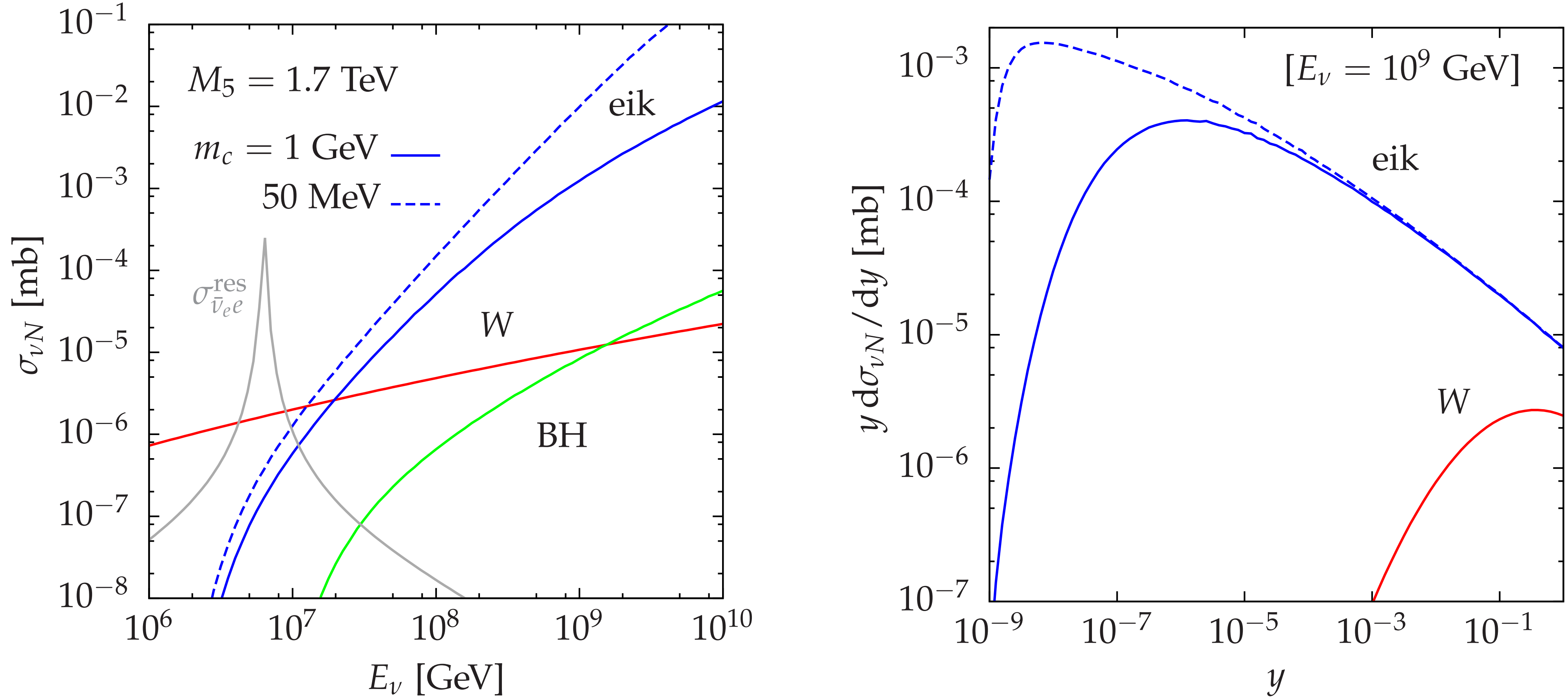
- Astrophysical and cosmological bounds:
  evaded when first KK mode $\sim m_c \gtrsim 50$ MeV

- Collider bounds:
  from BH (high multiplicity events and large MET) $\Rightarrow M_5 \gtrsim 1.5 - 2.4$ TeV [LEP]
  BUT model dependent (fermion localization in extra dimension)
  and ultraforward physics remains unconstrained

Ingredients | Cross sections

- Standard Model (νN) interactions: $\sigma_{\text{int}} = \sigma_{\nu N}^{\text{CC}}$ (W–exchange), $\sigma_{\nu N}^{\text{NC}}$ (subdominant)
  (and $\sigma_{\bar{\nu}_e e}^{\text{res}}$ at $E_\nu = M_W^2/(2m_e) \sim 6.3$ PeV)

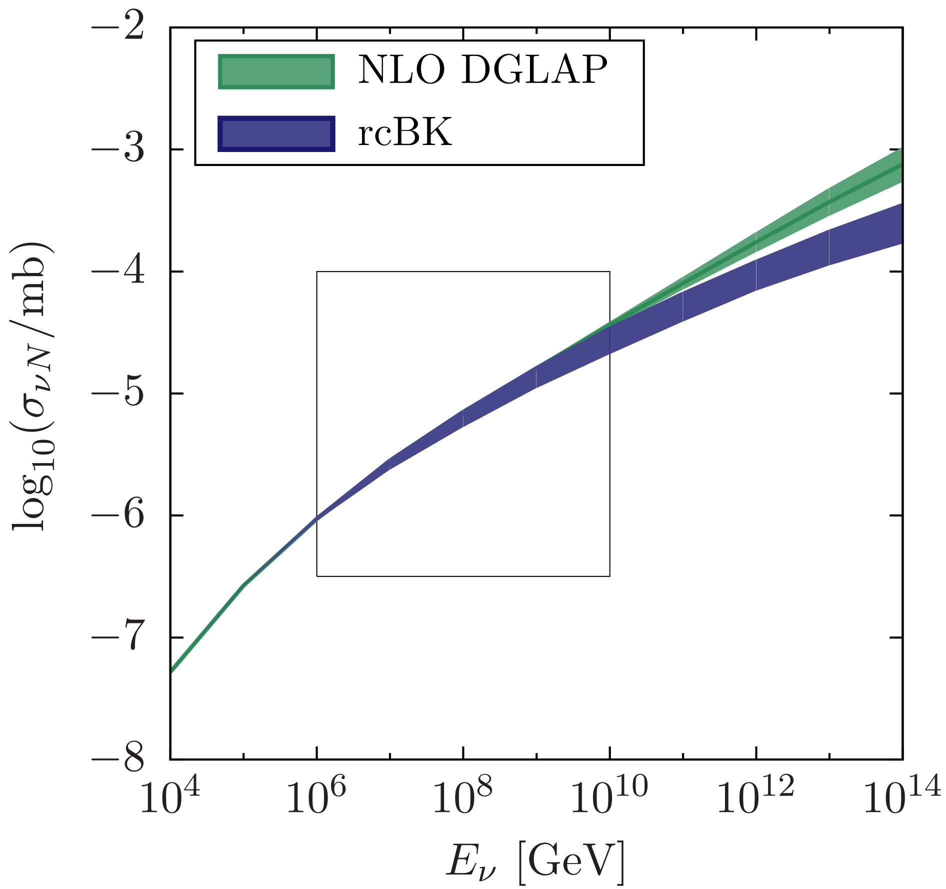
- Eikonal (νN) interactions: $\sigma_{\text{int}} = \sigma_{\nu N}^{\text{eik}}$ [large for $E_\nu \gg M_5^2/(2m_N) \gtrsim 3$ PeV]



Ingredients **About SM νN uncertainties**

[Albacete, JI, Soto-Ontoso: 1505.06583]

- At UHE, Bjorken $x \lesssim 10^{-7}$ is probed.
  Compare DGLAP (usual) to BK (includes saturation effects)

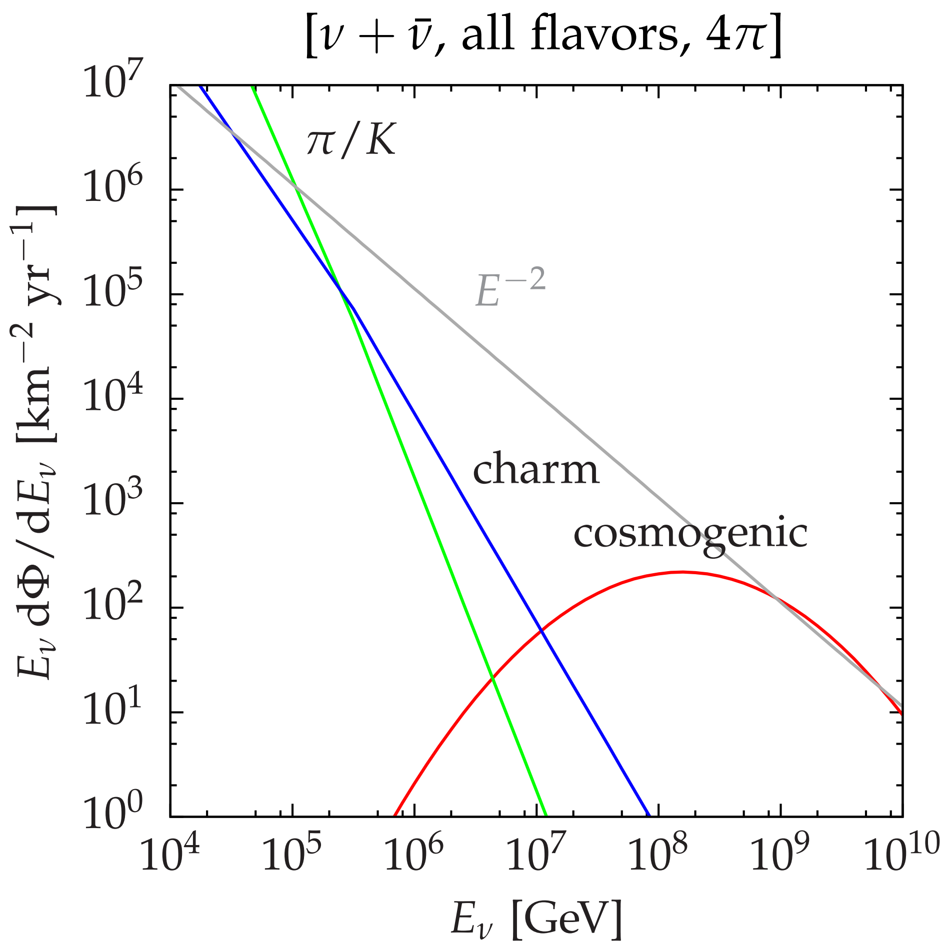


$\Rightarrow$ $\sigma_{\nu N}$ can be reduced by up to $\sim$ 50% at 10^{10} GeV

Ingredients | Neutrino fluxes

		$(\nu_e : \nu_\mu : \nu_\tau)_\oplus$
Atmos	π/K dcys ($\sim \cos^{-1}\theta_z$)	$(1:17:0)$
	Charm decays*	$(48:48:2)$
Astro*	Cosmogenic	$(1:1:1)$
	E_ν^{-2}	$(1:1:1)$

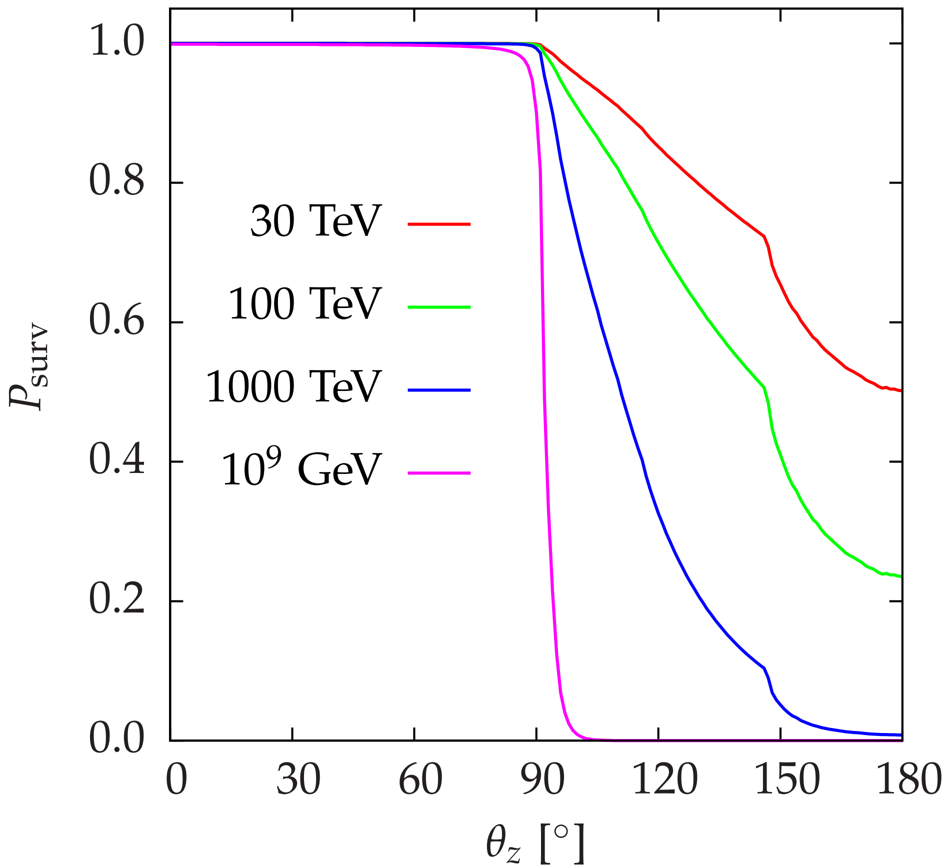
* isotropic



Ingredients **Survival probability**

- Neutrinos *stopped* by CC interactions and (for $E_\nu \gtrsim 10^9$ GeV) BH formation

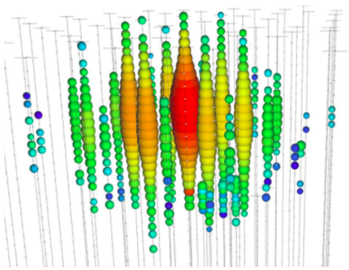
$$P^{\nu}_{\text{surv}}(\theta_z, E_\nu) = \exp\left\{-N_A\sigma(E_\nu)\int \rho_\oplus(\theta_z)\mathrm{d}\ell\right\}, \quad \sigma = \sigma^{\text{CC}}_{\nu N} + \sigma^{\text{BH}}_{\nu N}$$



Earth opaque at UHE for $\theta_z \gtrsim 90°$

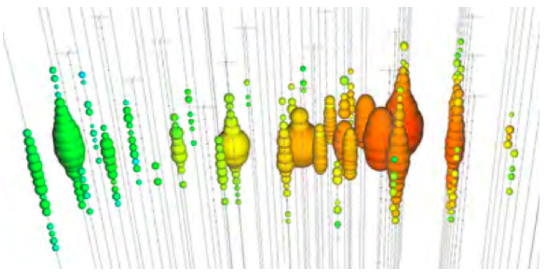
Ingredients | Showers vs Tracks

- Deposited energy



Showers (by electrons and hadrons)

$N_{\nu_i,\mathrm{NC}}$; $E_{\mathrm{sh}} = yE_\nu$	
$N_{\nu_e,\mathrm{CC}}$; $E_{\mathrm{sh}} = E_\nu$	$N_{\nu_i,\mathrm{eik}}$; $E_{\mathrm{sh}} = yE_\nu$
$N_{\nu_\tau,\mathrm{CC-had}}$	NP $\Rightarrow$ showers only
$N_{\nu_\tau,\mathrm{CC-electrons}}$	



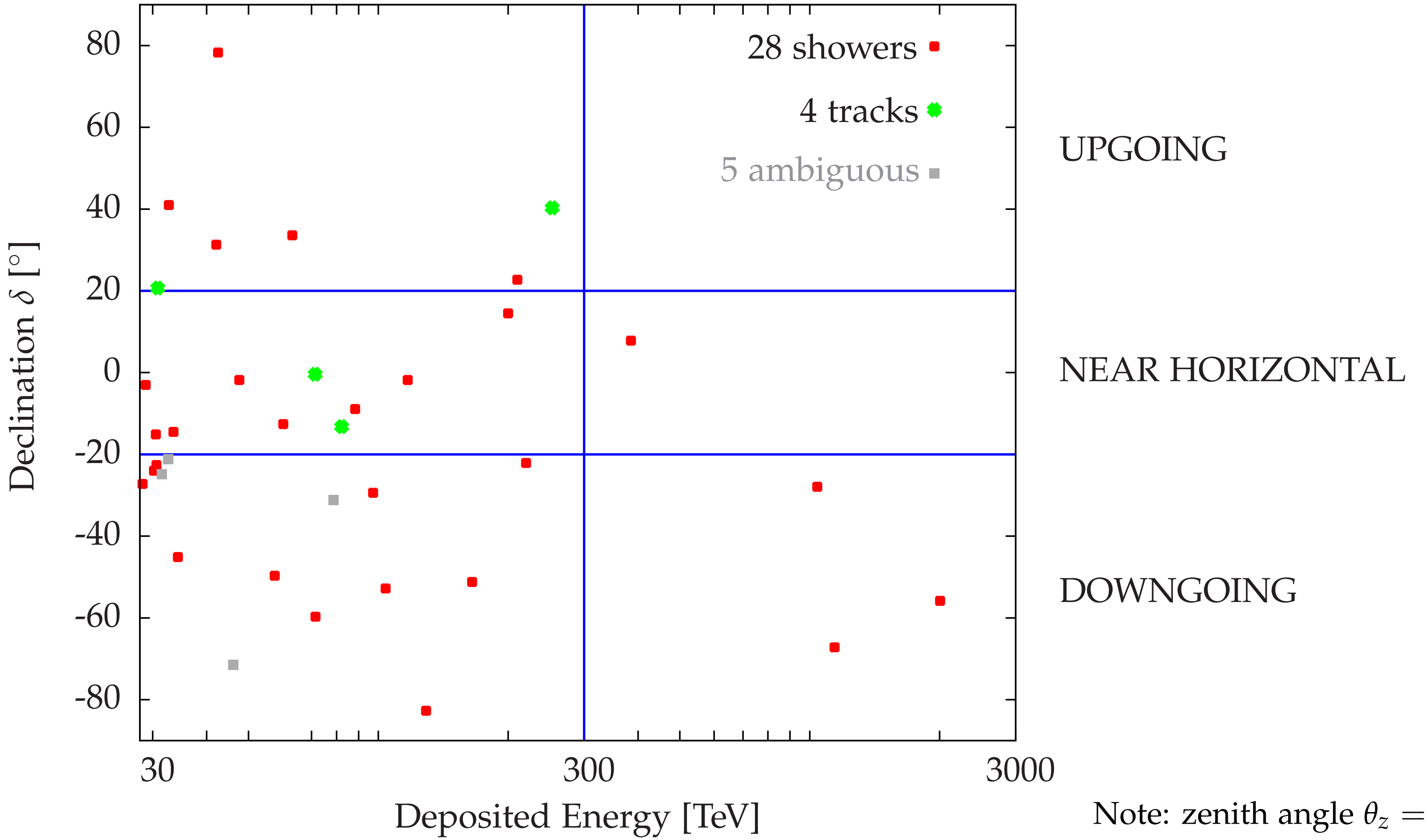
Tracks (by muons)

$N_{\nu_\mu,\mathrm{CC}}$; $E_{\mathrm{tr}} = yE_\nu$	$N_{\nu_\mu,\mathrm{eik}} = 0$
$N_{\nu_\tau,\mathrm{CC-muons}}$	

Our analysis

- 2×3 bins of energy and angle

3 angular bins ($\Delta \cos \theta_z \approx 2/3$) $\Rightarrow$ disentangle cosmogenic from E_ν^{-2} neutrinos



Note: zenith angle $\theta_z = 90° + \delta$

Our analysis

Tracks from atmospheric ν

	Data	Atm			Data	Atm			
Tracks	2	0.8			0	0.0			UPGOING

	Data	Atm			Data	Atm			
Tracks	2	3.5			0	0.0			NEAR HORIZONTAL

	Data	Atm			Data	Atm			
Tracks	0	0.2			0	0.0			DOWNGOING

30 – 300 TeV   300 – 3000 TeV

- Number and distribution of tracks *roughly* explained by atmospheric neutrinos (4.5 expected, 4 observed)

Our analysis | Showers from atmospheric ν

	Data	Atm			Data	Atm			
									UPGOING
Showers	5	2.7			0	0.0			
									NEAR HORIZONTAL
Showers	8	5.9			1	0.2			
									DOWNGOING
Showers	11	0.6			3	0.0			
	30 – 300 TeV				300 – 3000 TeV				

- Shower excess (astrophysical) especially significant in downgoing direction:

$11 - 0.6 = 10.4$ (30 – 300 TeV)	$3 - 0 = 3$ (30 – 300 TeV)

Our analysis **Astrophysical E_ν^{-2} hypothesis**

	Data	Atm	E_ν^{-2}		Data	Atm	E_ν^{-2}		
Tracks	2	0.8	0.6		0	0.0	0.1		UPGOING
Showers	5	2.7	3.6		0	0.0	0.7		
Tracks	2	3.5	1.5		0	0.0	0.5		NEAR HORIZONTAL
Showers	8	5.9	6.4		1	0.2	2.6		
Tracks	0	0.2	1.6		0	0.0	0.6		DOWNGOING
Showers	11	0.6	6.5		3	0.0	2.9		
	30 – 300 TeV				300 – 3000 TeV				

- Provides extra (✓) showers and extra (?) tracks: $\sim$ 4 or 5 showers per track
- Same number extra showers from downgoing and near-horizontal directions
- How about Glashow resonance: $\sim$ 2 evts expected at $E \sim 6$ PeV, none observed

Our analysis | NP and cosmogenic neutrinos hypothesis

	Data	Atm		NP	Data	Atm		NP	
Tracks	2	0.8		0.0	0	0.0		0.0	UPGOING
Showers	5	2.7		0.0	0	0.0		0.0	
Tracks	2	3.5		0.0	0	0.0		0.0	NEAR HORIZONTAL
Showers	8	5.9		4.2	1	0.2		1.9	
Tracks	0	0.2		0.0	0	0.0		0.0	DOWNGOING
Showers	11	0.6		8.0	3	0.0		3.5	
	30 – 300 TeV				300 – 3000 TeV				

- Provides no extra tracks (✓)
- Double extra showers from downgoing that from near-horizontal directions

Our analysis | Comparison of both hypotheses

	Data	Atm	E_ν^{-2}	NP	Data	Atm	E_ν^{-2}	NP	
Tracks	2	0.8	0.6	0.0	0	0.0	0.1	0.0	UPGOING
Showers	5	2.7	3.6	0.0	0	0.0	0.7	0.0	
Tracks	2	3.5	1.5	0.0	0	0.0	0.5	0.0	NEAR HORIZONTAL
Showers	8	5.9	6.4	4.2	1	0.2	2.6	1.9	
Tracks	0 (5)	0.2 (7.6)	1.6	0.0	0	0.0	0.6	0.0	DOWNGOING
Showers	11	0.6 (0.8)	6.5	8.0	3	0.0	2.9	3.5	
	30 – 300 TeV				300 – 3000 TeV				

- Likelihood (E_i = prediction, X_i = data)

$$-2\ln\lambda = \sum_i^{\text{nbin}} 2\left(E_i - X_i + X_i \ln\frac{X_i}{E_i}\right) = \begin{cases} 5.9 \ \ (7.3) \text{ for NP} \\ 15.4 \ (15.1) \text{ for } E_\nu^{-2} \end{cases} \text{excl. (incl.) 5 } \textit{ambiguous } \mu$$

Conclusions

- So far, our scenario with NP + cosmogenic neutrinos provides a better fit to data

  [TeV gravity model is a particular realization of generic type of models where UV physics is dominated by long-wave lengths: *classicalization*] [Dvali et al, '10]

- How to discriminate between both interpretations?
  - Multiple bangs?
  - Glashow resonance?

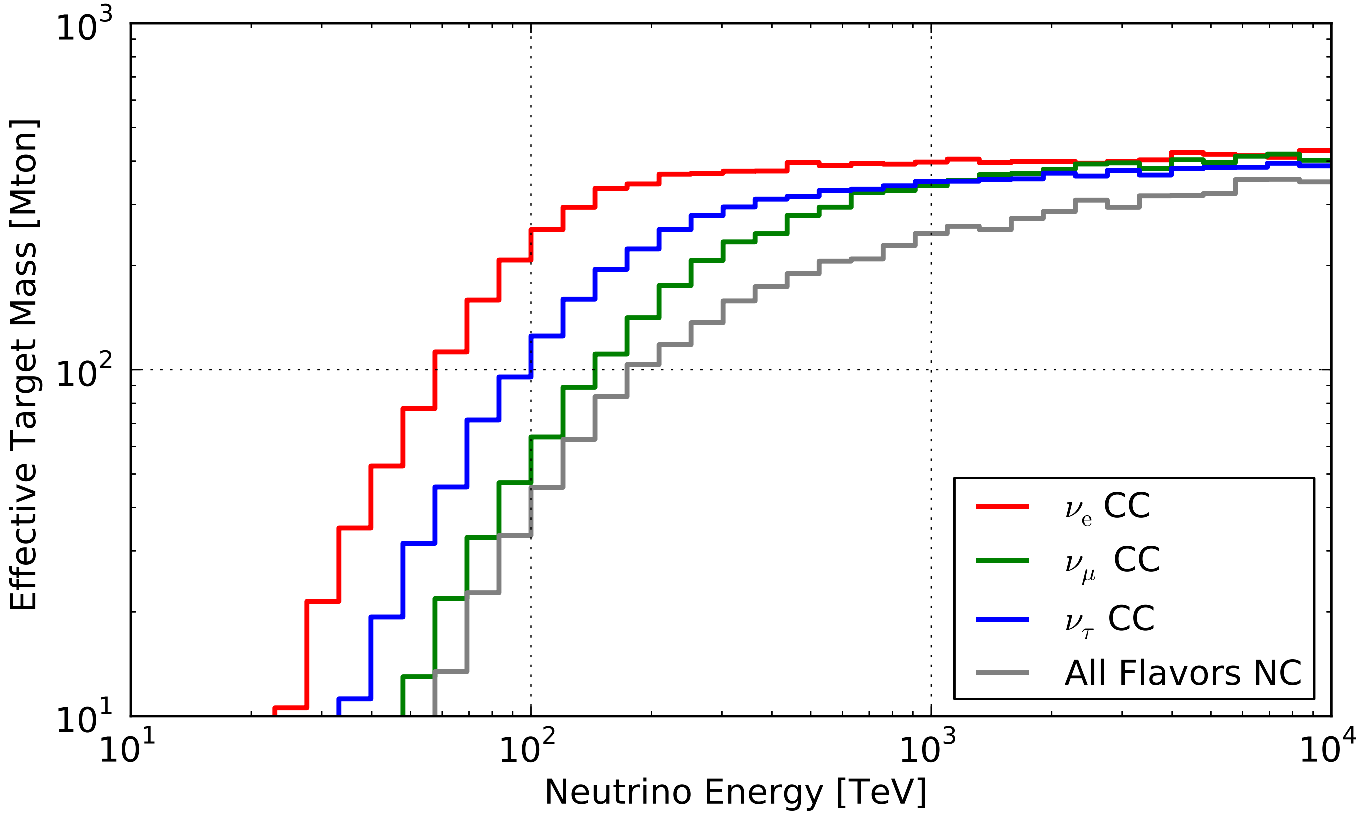
- Wait for **more** statistics!
  - Check in particular the ratio of downgoing to near-horizontal showers:

$$(2{:}1) \text{ for NP versus } (1{:}1) \text{ for } E_\nu^{-2} \text{ (lower energy SM int)}$$

BACKUP

Ingredients — Effective IceCube mass

- The effective mass is interaction, flavor and energy dependent: [IceCube '14]



$\Rightarrow$ About 500 Mton, that is 0.5 km^3 of ice, at ultrahigh energy